Water Security 10 (2020) 100061

Contents lists available at ScienceDirect

Water Security

journal homepage: www.elsevier.com/locate/wasec

Climate informed seasonal forecast of water availability in Central Asia: State-of-the-art and decision making context

Lars Gerlitz*, Sergiy Vorogushyn, Abror Gafurov

GFZ German Research Centre for Geosciences, Hydrology Section, Potsdam, Germany

ABSTRACT

Central Asia is characterized by a continental climate and a pronounced inter-annual variability of precipitation and discharge. In the past, hydro-climatological droughts led to serious water shortages, resulting in crop shortfalls, significant economic loss and inter-state political tensions. Robust forecasts of anomalous climatic and hydrological conditions may reduce regional vulnerability to hydro-climatic extremes and thus can serve as a scientific basis for national and trans-national water management. Based on a synthesis of international literature and on our decadal-long experience in the region, we systematically review the scientific progress in seasonal forecasting and evaluate the potential for a scientifically-informed water management. Additionally, we discuss to what extent the scientific progress meets the requirements of stakeholders and reveal major obstacles for a sustainable knowledge transfer. Our review shows that exceptionally skillful discharge forecasts for the agricultural relevant vegetation season can be derived by means of statistical models taking remote-sensing based estimations of the snow coverage in the Central Asian mountain regions as independent covariates. The consideration of global climate indices, in particular El Niño, allows to extend the forecast lead-times. However, decision makers are often not aware of the scientific progress and its implications for improved water management. Despite the continuous international effort with regard to knowledge transfer and capacity development, modernization at Central Asian water management institutions is proceeding slowly. A continuous engagement in the field of capacity development and knowledge dissemination at various institutional levels (including academia, forecast centers and water management institutions) appears necessary in order to stimulate a multi-disciplinary network and to support a sustainable regional collaboration in the water sector.

1. Introduction

Central Asia, comprising the five former Soviet countries Kazakhstan, Kyrgyzstan, Uzbekistan, Tajikistan, Turkmenistan, and Afghanistan (Fig. 1a), is frequently referred to as a prime example of inadequate water management and thus has been in the spotlight of the international water science and management community during recent decades [1–4]. The region covers the two endorphic river basins of Syrdarya and Amudarya, draining to the Aral Sea. Due to the continental climate, Central Asia is characterized by water scarcity and a pronounced seasonal and inter-annual variability of precipitation [5–9]. Water resources in Central Asia are mainly formed in the high mountain regions of Tien Shan, Pamir and Hindukush, where cold season (Nov-Mar) temperatures remain below zero and precipitation sums exceed 500 mm, which represents more than 50% of the annual precipitation amount (Fig. 1 b, c & d). In contrast, arid to semi-arid conditions prevail in the Central Asian plains throughout the year, i.e. evaporation distinctly exceeds the annual precipitation amounts. Since winter and spring precipitation falls predominantly as snow and is released to the rivers during summer, the mountain regions act as a water storage for the summer months and are often referred to as “Water Towers” [10–13]. The headwater catchments of the Central Asian rivers are characterized by a distinct seasonal cycle with discharge maxima during the summer season (Fig. 1e). Summer runoff is controlled by snow and glacier melt [14–16], which is responsible for up to 50% of the seasonal discharge in glacierized catchments [11,17]. A significant contribution of groundwater to summer discharge has also been estimated, while the contribution of summer rainfall has been found to be below 20%. Hill et al. [17] show that groundwater recharge is strongly dominated by meltwater resources, which underlines the importance of the Central Asian winter climate for water availability and surface runoff during the subsequent vegetation period.

The mountainous countries, in particular Kyrgyzstan and Tajikistan, are located in the zone of water generation, while Kazakhstan, Uzbekistan, and Turkmenistan rely on water supply from upstream. This unique physio-geographic and hydrologic setting raises challenges in the field of trans-boundary water management and regional political cooperation. Throughout the region, water provides valuable input to households, farming and for food security in rural areas. In the downstream countries Uzbekistan, Turkmenistan and Kazakhstan, the cultivation of water-demanding crops (cotton, rice, wheat) is of great importance for the national economies [18,19]. However, the upstream countries Kyrgyzstan and Tajikistan increasingly use the water for hydropower production in winter, which leads to reduced water supply during summer season [20,21]. Plans for an expansion of hydropower production in the head water catchments of Amudarya are currently

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* Corresponding author.
E-mail address: lars.gerlitz@gfz-potsdam.de (L. Gerlitz).

https://doi.org/10.1016/j.wasec.2020.100061
Received 22 July 2019; Received in revised form 13 March 2020; Accepted 13 March 2020

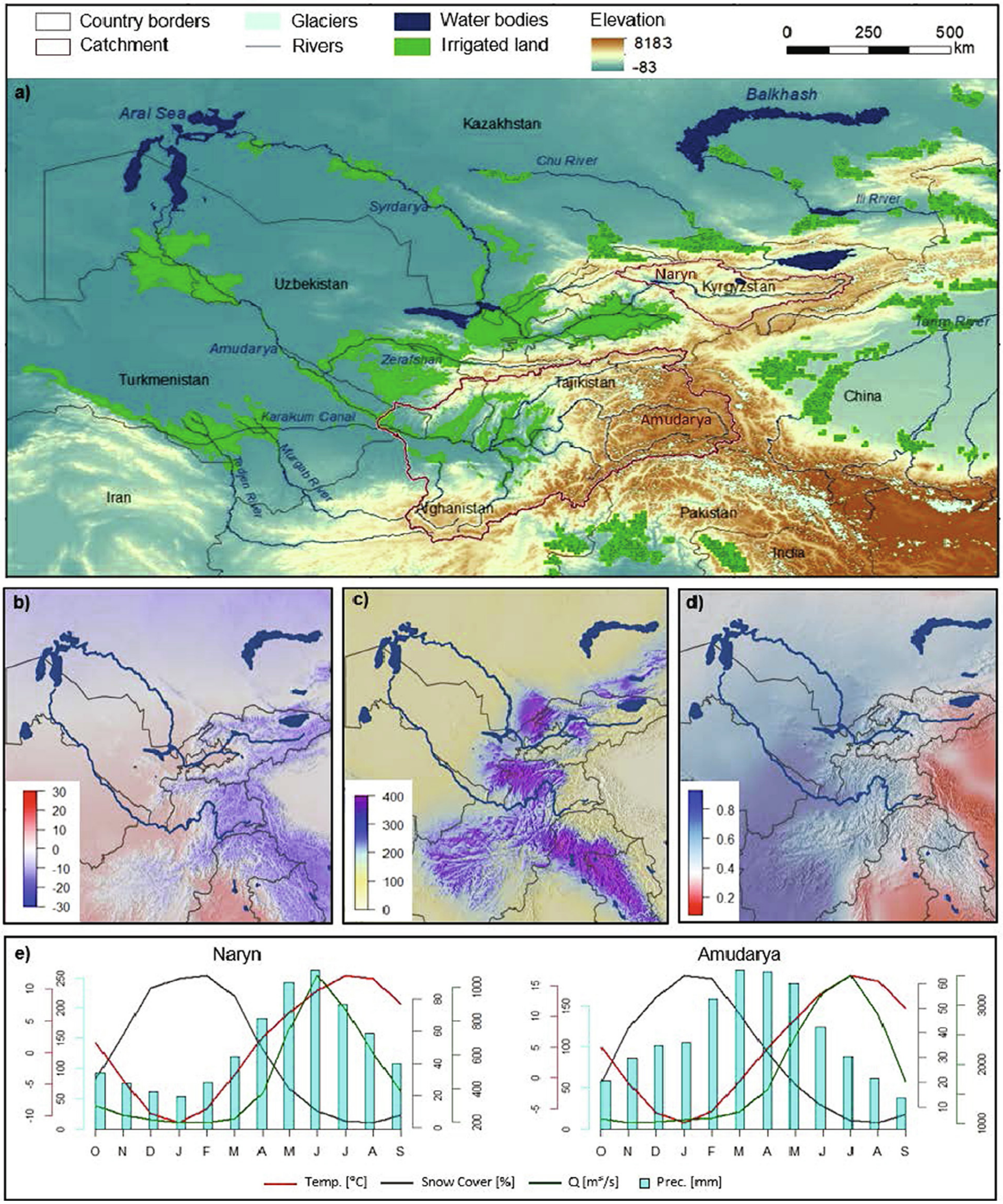

Fig. 1. Major characteristics of the Central Asian region: a) Elevation, water bodies, irrigated land. b) Mean Temperature [°C] during the cold season (Nov-Mar). c) Mean seasonal precipitation [mm]. d) Share of cold season precipitation in the annual precipitation amount. e) Seasonal cycle of catchment average precipitation, temperature, snow coverage and monthly mean discharge for the Naryn and Amudarya basins (Data: CHELSA-Climatologies at high resolutions, http://chelsa-climate.org, snow cover is based on MODIS observations. Streamflow records were provided by the Central Asian hydro-meteorological services).

discussed in Afghanistan [22]. This competitive system is often referred to as "water-food-energy nexus" [23]. The unbalanced water demand and the inefficient water use form the core of the water problem in Central Asia [24].

The inter-annual variability of water availability is challenging and impedes long-term planning in regional water management. The prolonged drought from 1999 to 2001 as well as the drought event of 2007/2008 had far reaching consequences, such as region wide crop failure, loss of livestock, breakdown of hydropower electricity production and an increase in diseases [5,25]. Likewise, climate induced refugee movements and trans-national conflicts on water allocation and management have been reported [5,25,26]. With a view to climate change and population growth, these water related challenges might exacerbate in future [10,27].

During recent years several international projects, among others the German Water Initiative for Central Asia ("Berlin Process"), have been supporting sustainable water management strategies in Central Asia and called for an improved trans-national cooperation in the water sector. The elaboration and implementation of an 'Integrated Water Resource Management' plan for Central Asian catchments, i.e. for the rivers Syrdarya and Amudarya, has been in the focus of the international effort [28]. However, decision-making processes at different levels require robust information on the quantity of available water resources [29]. Thus, the quantification of water resources in the high mountain regions is an important prerequisite for trans-national and trans-sectoral negotiations on water allocation. For instance, robust hydro-climatological predictions enable an improved management of water reservoirs and can reduce the risk of trans-national conflicts. Furthermore, a precise seasonal and sub-seasonal forecast of summer water availability is required for the prediction of agricultural yields and in order to adapt the national agricultural strategies to anomalous hydro-climatic conditions.

Based on a thorough review of international literature and our experience in the region, we summarize the current understanding of hydrological and atmospheric processes resulting in inter-annual variations of water availability in Central Asia. We systematically review the recent scientific progress in the field of discharge and precipitation forecasting (section 2) and assess the potential of seasonal forecasting applications for a scientifically-informed water management (section 3). We address the question, to what extent the scientific progress meets the requirements of stakeholders and reveal the major obstacles for a sustainable knowledge transfer and a fruitful collaboration between the international scientific community and regional water management institutions (section 4). Finally, we elaborate potential solutions for an improved scientific cooperation in the field of water research and management in Central Asia.

2. Scientific progress in seasonal forecasting

The regional hydrology of Central Asia is closely linked to annual cycle of the major atmospheric circulation modes over Eurasia, which influence the regional climate and interact with the expressed topography. Central Asia is influenced by both, temperate and (sub-) tropical circulation regimes, however their influence varies throughout the year. Particularly the prevailing westerly winds have been identified as an important moisture source, as they control the tracks of extra-tropical disturbances from the Atlantic and the Mediterranean Sea into the continental region of Central Asia [6,7,30,31]. Mariotti [8] illustrates that a northward current over the Arabian countries transports tropical air masses from the Arabian Gulf into Central Asia and represents an important additional moisture source. The southern parts of Central Asia, particularly the windward slopes of the Karakoram and Hindukush mountain ranges, receive high amounts of winter precipitation (DJF), which reaches up to 60% of the total annual sum (Böhner 2006; [32,33]). During spring the zone of maximum precipitation migrates northward, reaches the Pamirs in March and continues to Tien Shan in April/May [32,34].

During winter and spring season, high precipitation amounts result in a substantial accumulation of snow in the mountain regions [9,11,13]. In March and April, the snowmelt period starts and the stream flow increases instantly (Fig. 1 e). During late summer, the role of glacier melt increases 11,16. While the Amudarya headwater catchment receives a precipitation maximum in winter and spring, which leads to a clear temporal separation of the snow accumulation and the peak discharge period, the headwater catchment of Syrdarya (Naryn, see Fig. 1a) is additionally influenced by summer precipitation. Based on a conceptual temperature index model, Armstrong et al. [35] quantify the contribution of snow melt for the annual discharge of Sydarya and Amudarya to 72% and 65%, respectively. Based on remote sensing derived snow cover observations Dietz et al. [36] and Tang et al. [37] show that snow cover duration and snow cover area over Central Asia are subjected to a large seasonal and inter-annual variability. The variability and change of the snow cover characteristics in the high mountain regions have been shown to directly affect the hydrological regimes of the Central Asian rivers [16,38].

2.1. Seasonal discharge forecasts

Seasonal discharge forecasts for the summer period in Central Asia are in general rely on the fact that water resources are accumulated during winter season in the high elevations of the Tien Shan and Pamir mountain ranges and are released during the subsequent vegetation period. The comparatively small contribution of summer precipitation is generally neglected. The concept of a temporal separation of water accumulation and release has already been well acknowledged by Soviet water managers in the 1960s, when regular field expeditions and helicopter flights were conducted to assess the snow accumulation [39,40]. While traditional forecasting techniques were largely based on the subjective evaluation of point-scale snow cover information under consideration of lookup tables, quantitative models, including physically based hydrological models and statistical approaches, emerged during recent decades. Borovikova et al. [41] applied the conceptual hydrological model AISHF (Automated Information System for Hydrological Forecasts) for the short-term and seasonal runoff forecast in the Amudarya basin. They simulate snow fall as a function of average precipitation and its elevational dependence and assess snow accumulation as the balance between the income and the (temperature dependent) loss of solid precipitation during the winter season. In a forecast mode, glacier and snow melt are simulated based on meteorological data from analogue years. Due to the high data requirements of physically based models, the majority of recent studies applies statistical forecasting techniques, which are less data demanding. These utilize the relationship between winter precipitation, temperature or snow accumulation, as an indicator of catchment wetness, and the mean river discharge during the subsequent summer season.

Traditionally, Central Asian water management institutions rely in their forecasts on hydro-meteorological observations from representative monitoring stations. However, the hydro-meteorological network in Central Asia degraded significantly during the economic crises of the 1990s [42]. Although the national hydro-meteorological services with substantial support by international organizations made progress in re-establishing the monitoring network during recent years [43]; previous programs by WorldBank, Swiss Federal Office for Foreign Economic Affairs, Swiss Development Cooperation and USAID), the analysis of the spatial and temporal climate variability at the regional scale based on station data remains challenging. Further in-situ observations are often not readily exchanged between Central Asian water management institutions due to regional data protection laws and interstate political tensions, which leads to difficulties, especially in trans-national catchment areas [41]. Nowadays, freely available and spatially complete data sets derived from climate modelling and remote sensing can enable a cross-border assessment of water availability.

For Syrdarya, 85% of the inter-annual variability of summer discharge could be explained by a linear regression taking the catchment average precipitation sum during the preceding December–April period as an independent covariate based on ERA-15 reanalysis (Schär et al., 2004). For Amudarya, the explained variance amounted to 25% only, possibly due to a lower quality of the ERA-15 precipitation data set over southern Central Asia, a stronger influence of glacier melt, or water abstraction for irrigation purposes. Dirren [44] re-evaluate the potential of reanalysis data for seasonal runoff forecasting based on the ERA-40 reanalysis, and found a significantly improved skill for the Amudarya basin. Similarly, Barlow and Tippett [45] investigated the potential the NCEP/NCAR reanalysis to derive skillful runoff forecasts for the summer season. Seasonal mean discharge time series from 24 gauges in the Aral Sea basin were related to cold-season

(November–March) precipitation fields by means of a canonical correlation analysis. Particularly for gauges in the Syrdarya basin, an explained variance of 20 to 50% could be attained.

Recently the value of remote sensing based observations of winter precipitation and snow cover for seasonal forecasting applications has been emphasized. Dixon and Wilby [46] demonstrated the skill of TRMM precipitation estimates during the cold season (October to March) to explain 65% of the inter-annual discharge variability between 1999 and 2010 by a univariate forecast model. The integration of temperature and antecedent discharge further improved the forecasting skill. Pertzinger et al. [47] and Baumgartner et al. [48] show that NOAA-AVHRR snow cover observations could capture 86% of the seasonal inflow variability into the Charvak reservoir in Uzbekistan. Nowadays, fully automated tools for image acquisition and processing, including cloud removal, reached the operational level [49–51] resulting in spatially coherent snow cover information. Apel et al. [52] utilized cloud eliminated snow cover data along with station-based observations of precipitation, temperature and antecedent discharge in winter and spring to predict mean warm season (April-September) discharge in 13 Central Asian basins with catchment areas ranging from 240 to 290.000 km^2. The predictor set was extended by multi-monthly means of the individual predictors, as well as composites of the predictors in order to account for non-linear statistical relations and predictor interactions. The results indicate a high predictive skill of the employed predictors already in January (with explained variance of 60–80% for most of the catchments) and a continuous improvement of the forecast during the spring season (with explained variance of 80–90% in April). Snow cover related predictors have been shown to be particularly powerful for most catchments. Recently, aiming at a higher temporal resolution of the discharge forecasts (e.g. at monthly scale) the potential of elevation restricted snow cover information for sub-seasonal forecasting purposes has been evaluated. Gafurov et al. [51] show, that snow cover dynamics in different elevation bands serve as skillful predictors for the prediction of mean monthly discharge during the early summer season. In late summer, when glacier melt dominates the runoff generation, the predictive power of snow cover decreases significantly.

Although the availability of remote sensing based observations of precipitation and snow cover is still limited to a short period and some of the employed algorithms might be susceptible to overfitting due to the high number of potential predictor combinations, the review emphasizes the added value of modern earth observation techniques in the field of seasonal hydrological forecasting. Meanwhile, new products derived from passive or active microwave remote sensing facilitate an assessment of the snow water equivalent (SWE) at a 25 km horizontal resolution and have been successfully evaluated for the Nothern Hemisphere [53,54]. Likewise, remote sensing based observations of the gravity field have been shown to be of great potential for the estimation of the natural water storage variability at the regional scale, as they represent an expression of the integrated water storage change on and below the Earth surface, including SWE, glaciation, soil moisture and groundwater [55,56]. Based on data from the Gravity Recovery and Climate Experiment (GRACE, 2002–2017) Apel et al. [57] show that gravimetric variations during the winter season serve as skillful predictors for warm season discharge predictions in large river basins, such as Amudarya. No significant forecast improvement could be detected at smaller scale.

Fig. 2 provides a schematic summary of the major predictor variables and the skill of frequently applied multi-linear forecasting techniques for the Central Asian headwater catchments of Amudarya and Naryn. Composite maps (Fig. 2 a, b c) suggest that vegetation periods with above average streamflow are preceded by higher precipitation sums and temperatures in winter and higher snow coverage in April. Correlations between the employed predictor variables and April-September discharge are consistently positive and mostly significant, particularly for the Amudarya catchment, which is characterized by a clear temporal separation of the high-precipitation and the high-discharge period (see Fig. 1). 82% of the inter-annual variance of mean seasonal discharge in the Amudarya catchment can be explained by a simple linear-regression model, taking November-March catchment average precipitation sums and temperature means, March snow cover fraction and antecedent discharge as independent variables. For Naryn, where summer precipitation constitutes a relevant portion of the annual sum, the forecast skill is lower (explained variance = 0.56), but still highly significant.

2.2. Seasonal forecast of winter precipitation

For the estimation of summer discharge in Central Asia, predictors are required that represent the state of water resources in high-elevation headwater catchments. However, these do not emerge before late spring and thus enable a forecast of summer runoff anomalies only a few months in advance. In order to extent the lead time of discharge predictions, robust climatic forecasts are required that allow predicting precipitation amounts and snow conditions during the winter season. Seasonal climate forecasts for the entire globe based on dynamical Atmosphere Ocean General Circulation Models (AOGCMs) are operationally provided by few meteorological research centres [58]. These models utilize the fundamental fluid dynamic equations and enable the prediction of large-scale climate conditions at various temporal scales [59,60]. Best results of dynamical climate forecasts are usually found in the tropics, where large-scale wind fields and associated moisture fluxes are strongly influenced by sea surface temperature anomalies [60–62]. Weisheimer and Palmer [63] test the reliability of the ECMWF-System4 Seasonal forecast ensemble on a coarse global grid and rate the performance from 1 (dangerous, misleading) to 5 (perfect). Their results prove a high skill of the ECMWF model for the forecast of winter precipitation in Central Asia, particularly for the prediction of droughts.

Due to their high computing requirements, AOGCM based seasonal forecast models are rarely applied in hydro-meteorological and environmental offices, particularly in developing and transition countries. Statistical forecasting techniques represent a less computation-intensive alternative, however, they require a profound understanding of hydro-climatic variations, associated large-scale atmospheric processes and their driving mechanisms in order to identify relevant predictor variables. Previous studies show, that both, tropical and westerly circulation modes simultaneosly influence the Central Asian climate, particularly during the moist winter and spring seasons. Weather types over Central Asia have been shown to represent a regional expression and superposition of tropical and extratropical circulation features that propagate into the target domain from western and southern directions, respectively [64]. Schiemann et al. [65] and Schiemann et al. [7] illustrate that hydro-climatic conditions over Central Asia are strongly influenced by the location and strength of the westerly jet stream. Gerlitz et al. [64] show that positive precipitation anomalies over Central Asia are frequently associated with the formation of a Rossby trough, which is usually well developed during the simultaneous positive state of the North Atlantic Oscillation and the East Atlantic/Western Russia pattern. Significant correlations of winter precipitation sums have been detected with well-known Euro/Atlantic circulation modes, such as the North Atlantic/Arctic Oscillation (NAO, AO), and the East Atlantic (EA), Scandinavian (SCA), Polar/Eurasian (POL/EUR) and East Atlantic/Western Russia (EA/WR) patterns [6,30,31,66].

Various studies illustrate that variations of the El Niño Southern Oscillation alter the intensity of tropical moisture fluxes into Central and South Asia [6,42,44,67]. The El Niño warm phase is associated with persistent positive pressure anomalies over the western Indian Ocean, resulting in intensified south-westerly moisture supply. Barlow et al. [68] argue, that especially the Sea Surface Temperature (SST) of the Indopacific Warmpool influences the regional circulation and associated precipitation anomalies over South-West Asia. La Niña conditions are shown to promote an anticyclonic anomaly over Central Asia,

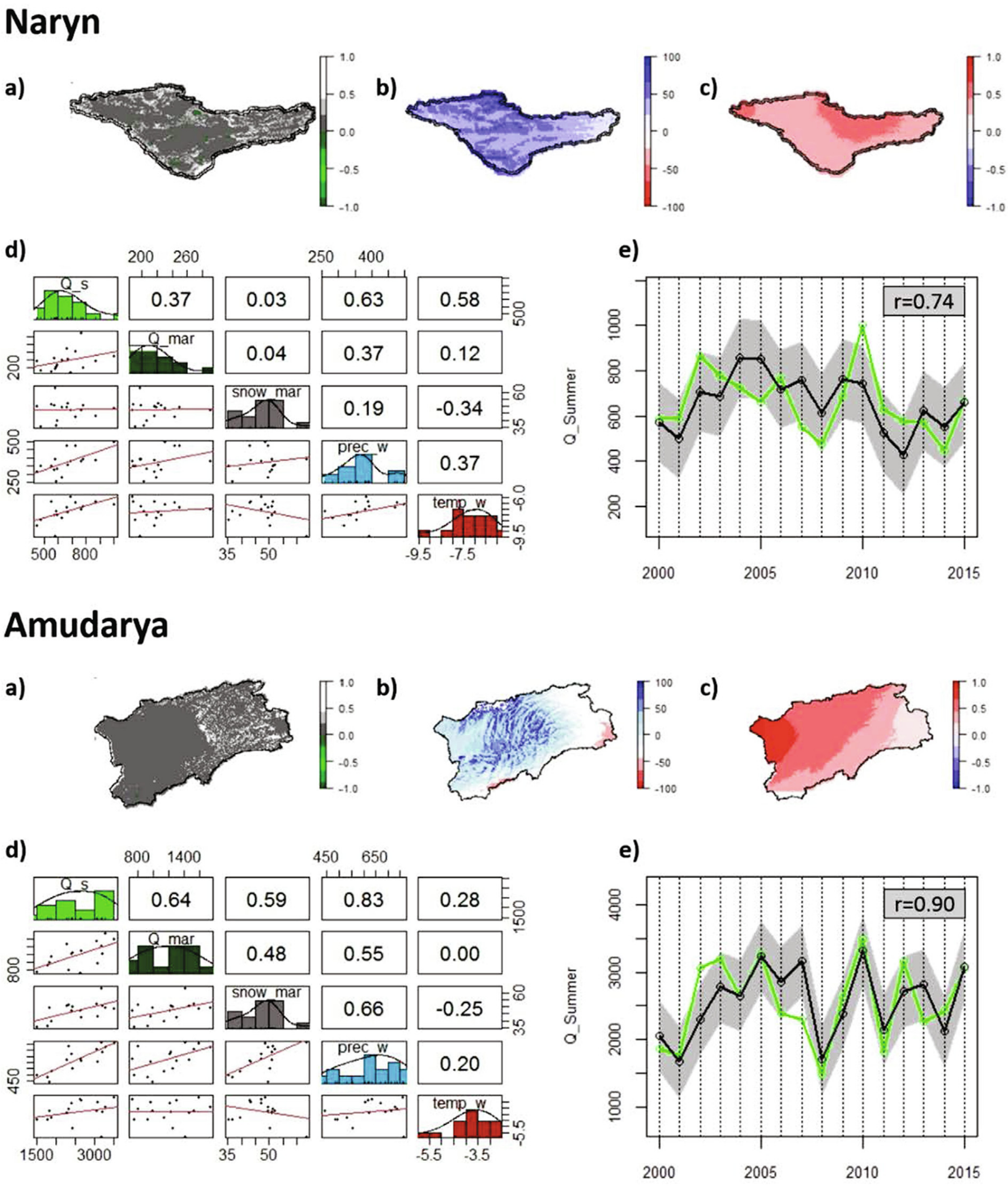

Fig. 2. Major predictors and their potential for the forecast of Apr-Sep mean discharge in the Naryn and Amudarya catchments. a,b,c) Composite maps of March snow cover [%/100], Nov-Mar precipitation [%] and temperature [°C]. Seasons are divided into two groups: high flow (Apr-Sep discharge > median) and low flow (< median). Composites indicate the difference between high flow and low flow conditions. d) Scatterplots and cross-correlations of selected predictors and Apr-Sep discharge (Q_s = Mean Apr-Sep discharge/Q_mar = antecedent discharge, March/snow_mar = monthly mean snow coverage in March in %/prec_w = extended winter precipitation, Nov-Mar/temp_w = extended winter mean temperature). e) Time series of observed (green) and cross-evaluated modelling results (black) and the prediction uncertainty interval comprising to 95% of the residual distribution.

resulting in precipitation suppressing subsidence. Syed et al. [10] and Syed et al. [30] show that enhanced winter rainfall over Afghanistan, Pakistan, Tajikistan and Uzbekistan is triggered by El Niño and intensified westerlies during the positive phase of NAO. Bastos et al. [69] conclude that moisture fluxes into Central Asia are controlled by a combined influence of the NAO and the EA-pattern. As ENSO is characterized by a low frequency variability and usually shows a seasonally persistent behavior, the potential of ENSO related indices for seasonal winter and spring precipitation forecasts has been emphasized for Central Asia. Severe droughts (e.g. 1989, 1999–2001 and 2008) have been shown to a at least partially triggered by La Niña conditions [5,28,64,68].

In general, due to the dominant influence of westerly wave tracks, their embedded synoptic features and associated moisture fluxes, the

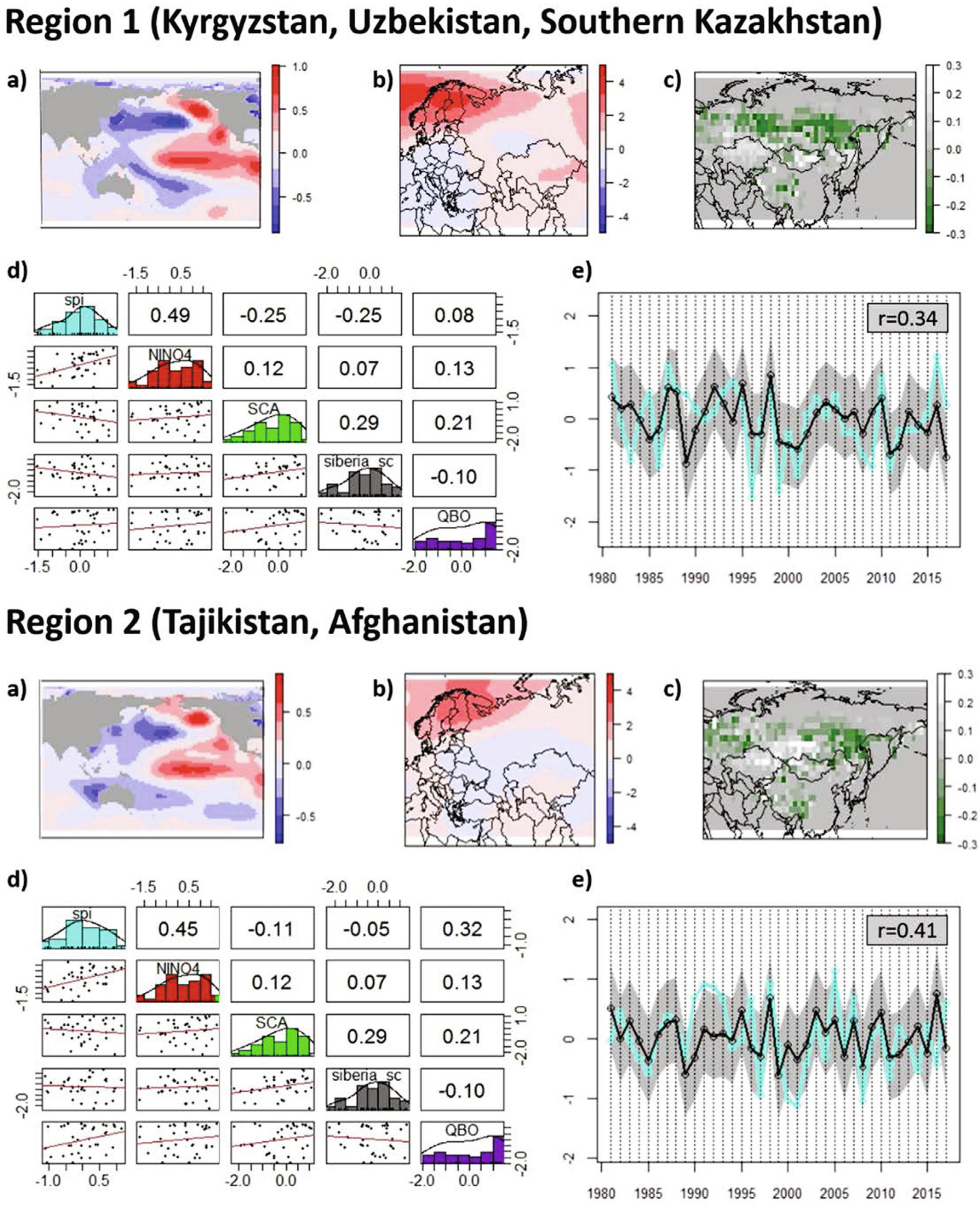

Fig. 3. Major predictors and their potential for the forecast of Nov-Mar precipitation anomalies for two Central Asian sub-regions. a,b,c) Composite maps of October SST [°C], October sea level pressure [hPa], October snow coverage [%/100]. Seasons are divided into two groups, high precipitation (> median) and low precipitation (< median), and averaged. Composites indicate the difference between high precipitation and low precipitation conditions. d) Scatterplots and cross-correlations of selected predictors in October and Nov-Mar SPI (SPI = standardized precipitation index, Nov-Mar/NIÑO4 = Mean SST anomalies in the ENSO4-region/SCA = Scandinavian pattern/Siberia_sc = snow cover extent over Siberia / QBO = Quasi Biennial Oscillation). e) Time series of observed (blue) and cross-evaluated modelling results (black) and the 90% prediction uncertainty interval.

skill of statistically based seasonal precipitation forecast models is rather low in extratropical regions. Particularly the prediction of regional wave tracks that determine the strength and position of the jet stream remains a challenge for both, dynamical and statistical forecasting approaches. Gerlitz et al. [32] developed a random forest based machine learning algorithm applied to global SST and climate reanalysis fields to forecast precipitation anomalies in Central Asia at monthly and seasonal scales. Although, the model identified several predictors, that are related to the Northern Hemispheric circulation characteristics, the explained variance of the model only slightly exceeds the skill of the

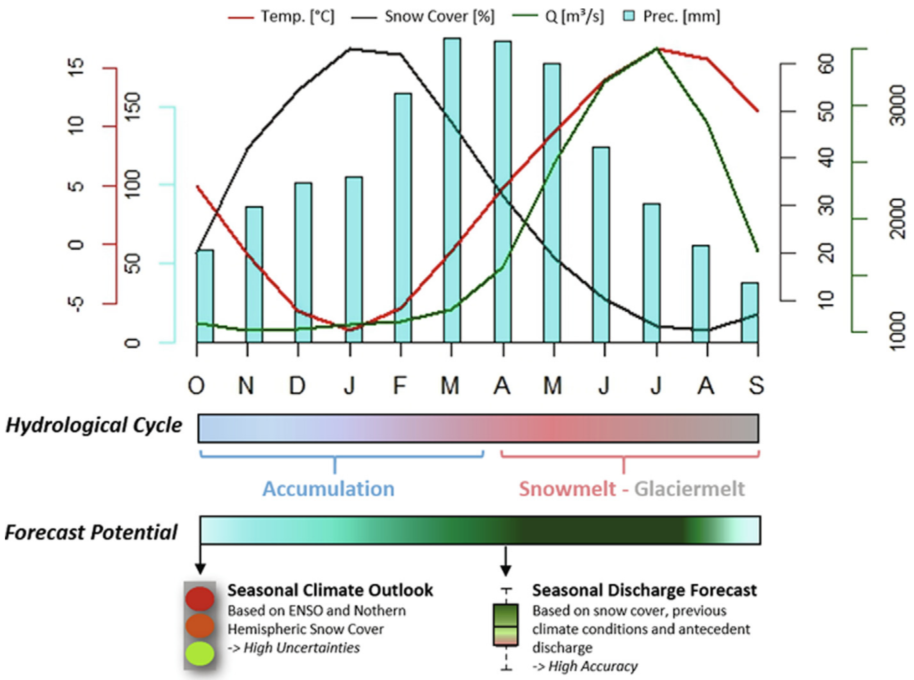

Fig. 4. Proposed two-tier forecast strategy: The upper panel shows the seasonal cycle of precipitation, temperature and discharge for the Amudarya river basin.

ENSO based forecast. Hartmann et al. [19], Hartmann et al. [70], Kundzewicz et al., [61] tested various predictors, including tropical and extratropical SST anomalies and pressure modes, for their skill in explaining monthly precipitation anomalies in the Western-Chinese Tarim Basin. Their results suggest an exceptional skill of SST anomalies in the Black sea and pressure anomalies in the core region of the Siberian High, which might indicate a dynamical modification of the winter circulation over Central Asia by varying initial and lateral boundary conditions. However, their validation strategy focusses on monthly precipitation anomalies and the skill drops significantly for the seasonal scale, which suggests an overfit of the statistical model due to a shifted seasonal cycle of predictor and predictant variables.

Various studies investigate the predictability of the large-scale Eurasian winter climate, particularly with regard to variations of the Arctic/North Atlantic Oscillation (AO/NAO). Auspicious progress has been made by considering snow cover anomalies in October as a predictor variable for the mean state of the Arctic Oscillation and associated climate anomalies during subsequent winter [71,72]. Both, observational and modeling studies indicate, that enhanced snow cover over Eurasia in October increases the surface albedo and triggers an early and strong formation of the Siberian High [73,74]. The consequential pressure gradient between Siberia and the Eastern Arctic provokes the formation of a persistent wave pattern, that propagates into the upper troposphere and results in a weakened stratospheric polar vortex [75,76]. A subsequent downward propagation of wave activity triggers the development of a negative NAO/AO. On the contrary, reduced snow cover over Eurasia provokes a strong zonal and positive NAO/AO conditions. Cohen et al. [71] illustrate that Eurasian snow cover in October serves as a skillful covariate for the prediction of winter temperature for large parts of the Northern hemisphere. Gerlitz et al. [6,23] show, that the Eurasian snow cover extent in October influences the regional circulation over Central Asia during winter season due to cascading processes at different spatial scales. At a regional scale, the positive state of AO/NAO during winter season favors the formation of a stationary Rossby trough over Central Asia, which is associated with a southward shift of the westerly jet stream and strongly positive precipitation anomalies, while the negative AO state favors dry conditions. Finally, the Quasi-Biennial Oscillation (QBO), a dominant and well predictable mode of variability in the tropical stratosphere has been identified as a potential predictor for the winter state of AO/NAO [65,77,78]. Observations show, that the positive phase of QBO is associated with a stronger and zonal oriented polar vortex, which favors the development of a positive AO. Negative correlations between the QBO index and sea level pressure during winter have been detected for large parts of Eurasia, including Central Asia [77].

Recently, Gerlitz et al. [6] analyzed the predictive potential of various covariates, including Indo-Pacific SST anomalies, Eurasian snow cover indices and Northern Hemispheric circulation modes in October for forecasting cold season (Nov-Mar) precipitation anomalies in Central Asian sub-regions. By means of a multi-variate linear regression approach, moderate forecast skills could be achieved for two sub-regions covering Uzbekistan, Kyrgyzstan and southern Kazakhstan (region 1) and Iran, Afghanistan, Tajikistan and northern Pakistan (region 2) for the period 1979 to 2017. While ENSO has been identified as the predominant predictor for both regions, the Eurasian snow cover extent in October and the Scandinavian pattern have been shown to improve the forecasting skill for region 1. For region 2 the Scandinavian Pattern and the Quasi Biennial Oscillation have been identified as skillful predictor variables. The results are exemplarily presented in Fig. 3. Composite maps of SSTs (Fig. 3 a) indicate a strong forcing of precipitation anomalies by variations of the El Niño Southern Oscillation for both regions, which is also manifested in highly significant correlations ($r > 0.4$, Fig. 3 c) between the regional average standardized precipitation index (SPI, Guttman [18] and the ENSO4 index. Further, positive precipitation anomalies are preceded by pressure anomalies that resemble the Scandinavian pattern. Bueh and Nakamura [79] show that SCA is characterized by a stationary behavior and a frequent reestablishment, which leads to a modification of Northern Hemispheric temperature and precipitation patterns at the seasonal scale. Gastineau et al. [80] and Bueh and Nakamura [79] further illustrate that snow cover variations over Eurasia are driven by SCA and its downstream wave tracks to a large extent. A statistically significant influence of Siberian snow cover on regional precipitation anomalies has been detected for region 1 only. Although, the results of the statistical model do not allow forecasting precipitation anomalies with high accuracy and large prediction intervals reflect the high uncertainty of climate predictions, they distinctly exceed the climatological forecast (i.e. the assumption of the climatological mean). Particularly drought events (e.g. in 1999–2001, 2007/2008 and 2011/2012) are well reproduced by the statistical model (see Fig. 3 f), which implies its potential for early warning applications.

Based on the summarized studies, we propose a two-tier forecasting approach at Central Asian water management institutions that includes a seasonal climate outlook and a hydrological prediction (schematically presented in Fig. 4). Based on the state of ENSO, Eurasian snow cover, SCA and QBO, a preliminary forecast of cold season precipitation anomalies and the associated accumulation of snow in Central Asian high mountain regions appears feasible by October. Although, the forecast is subjected to large uncertainties and robust predictions are only achieved at the regional scale, it enables a first assessment of the hydrological drought risk in the following vegetation period. In March/April, when the snow accumulation period ends, statistically based discharge forecasting approaches using remote sensing observations of snow cover and climate reanalysis appear to be highly suitable for practical applications.

3. Application of seasonal forecasting for water management in Central Asia

The rural economies of Central Asia are vulnerable to hydrological extremes, particularly to summer droughts, but also to floods, mudflows and landslides during the snow melt season [81,82]. This vulnerability has been recognized already during the Soviet past and substantial effort had been made to promote scientifically-informed decision-making in the water sector. Regular snow monitoring campaigns were already undertaken in the late 1960s [39,40]. In the 1980s, when frequent droughts significantly affected the agricultural productivity and thus the regional economy, semi-quantitative seasonal forecasts of water availability were operationally provided by the Central Asian Hydromet service in Tashkent [83]. These forecasts were based on analogue years and look-up tables and, at that time, met modern scientific standards. The centralized political system of the former Soviet Union allowed to easily integrate forecast information into regional water management strategies. The Soviet ministry of water resources in Moscow, in cooperation with regional water management authorities in Central Asian republics, defined the monthly release quotas from larger reservoirs and adjusted the agricultural strategies based on the expected discharge of Amudarya and Syrdarya [83]. While the upstream republics Kyrgyzstan and Tajikistan were forced to ensure the water provision for agricultural production in the arid lowlands, Kazakhstan, Uzbekistan and Turkmenistan delivered fossil resources (especially coal and gas) and secured the energy supply in the mountainous regions [21,84,85]. After the independence of the Central Asian republics and the associated transition towards market oriented economies, conflicting interests in the field of water management emerged. Nowadays, the catchments of the major Central Asian rivers are trans-national and cover diverse economic and social settings, which leads to a significant increase of the number of stakeholders in the water sector. The consequential challenges to trans-national and cross-sectoral cooperation have been widely debated in literature [12,21,84,85] and are discussed by Sehring [85] in this special issue. The application of scientifically-informed decision-making has become much more complex under the altered political and economic conditions.

The national hydro-meteorological service centers, established after independence, are responsible for the systematic survey and the provision of hydrological and climatic information. Their official tasks comprise the maintenance of the national hydro-meteorological monitoring networks, the preparation of short-term weather forecasts and the elaboration of seasonal hydrological forecasts for the vegetation period [37,86]. In the framework of the Regional Research Network Central Asian Water (www.cawa-project.net), the seasonal forecasting techniques and strategies at the five national hydro-meteorological services were surveyed and their requirements were evaluated in 2014. While the national forecasting experts were not aware of the opportunities of seasonal climate predictions under consideration of global teleconnections, seasonal discharge forecasts were considered as priority tasks. Seasonal forecasts of summer discharge are operationally conducted in January and adjusted at a monthly scale. Final forecasts of water availability are provided at the end of March, i.e. just before the start of the vegetation season [52]. The survey revealed that the forecasting departments rely on outdated infrastructure and techniques and suffer from the degradation of the hydro-meteorological monitoring network during the economic crises of the 1990 s. Although a modernization is in progress at all national centers, the relevant hydro-meteorological observations are frequently available in paper format only [29,87] and seasonal forecasts are often based on analogue methods, such as look-up tables, scatter plots, and snowmelt-runoff modelling fed by scarce observations. An urgent need for an improvement of the forecast accuracy and an extension of lead-times has been emphasized by the regional experts. However, the capacity of regional universities and research institutions in the field of model development and applied statistics is fairly limited, resulting in a reluctance of methodological innovation and a lack of ambitious visions [37,87]. In general, the national services lack of a systematic framework for the generation, storage and provision of data [29,87] which impedes the exchange of information and the implementation of modern forecasting approaches.

Seasonal discharge predictions are communicated to national water management authorities, only. For instance in Uzbekistan, discharge estimations are used by the Ministry of Agriculture in order to adjust the national cultivation strategies. Likewise, the Uzbek Ministry of Emergency Situations requested snow cover maps in the past and estimated the risk of floods, landslides and avalanches based on the provided information (personal communication with Baumgartner, MFB GeoConsulting GmbH, World Bank Project “Saving the Aral Sea, subproject “Improvement of the Infrastructure at the Hydro-Meteorological Services in Central Asia”, 1996–2005). To date, seasonal forecasts are not provided to the media or published online. To the author’s knowledge, non-governmental stakeholders, such as water reservoir managers, farmers or private companies, do not have direct access to hydrologically relevant data and information. Although trans-national organizations, which are responsible for the negotiation of water allocation quotas (in particular the Interstate Commission for Water Coordination in Central Asia, ICWC, and the Water Basin Organizations of Syrdarya and Amudarya, WBO), have access to seasonal discharge predictions, their decision making processes remain intransparent and most likely do not sufficiently incorporate seasonal forecasts. Remarkably, predictable water shortages have led to breaches of bilateral water allocation treaties in the past (e.g. during the La Nina year 2008), resulting in political tensions, that could have been potentially avoided under consideration of hydro-climatological information [88,83].

Success stories from various regions [47,89–93] highlight that progress in the field of scientifically-informed water and climate impact management requires the establishment of an interdisciplinary and trans-sectoral stakeholder network, including scientists, forecasting experts, political decision makers and affected stakeholders. Such knowledge systems represent an important prerequisite for a sustainable cooperation, since they allow a continuous evaluation of the actual user demands and a corresponding adjustment of forecasting techniques and communication strategies. Particularly the development of secondary (user tailored) products, e.g. targeting at agricultural yield estimations or hazard and risk assessments, has been shown to significantly increase the societal benefit of seasonal forecasting applications. However, stakeholder networks require a robust institutional basis, including boundary organizations that connect experts, practitioners and decision makers. Although, the trans-national structure, in particularly the ICWC and its advisory board, the Scientific Information Center (SIC), appear suitable for strengthening the connection between science and political action, the institutional mandates and responsibilities are only vaguely defined [21,94]. The institutional ambiguities at both, local and regional scales, and the underdeveloped information channels make it difficult for the hydro-meteorological centers, to introduce their forecasts to a broader circle of users and thus to further contribute to sustainable water management.

Overall, the outreach of the seasonal discharge forecasts remains far below its potential, especially in the field of trans-national and trans-sectoral water management. Urgent improvements are required with regard to the applied forecasting techniques and the underlying data. Particularly in view of global warming, which will likely enhance the risk of hydro-meteorological extreme events in Central Asia, the hydro-meteorological centers will have to respond quickly to changing user needs. Therefore, scientifically and technically well-trained and self-reliant employees are needed, who are not yet sufficiently available to the national services.

4. Linking science and action – opportunities and obstacles for knowledge dissemination and capacity development

During the last three decades, various projects, all aiming at a sustainable and scientifically sound development of water management strategies in Central Asia, have been implemented by international organizations [11]; however only some of them excelled through a long-term commitment. Several international activities explicitly accentuated the potential of seasonal forecasting applications and early warning. For instance, the World Bank initiated the Aral Sea Basin Program, which targeted at a scientifically robust basis for trans-national water management in Central Asia, already in 1992 [95,96]. In cooperation with the Swiss Aral Sea project (1996–2005), the potential of earth observation technologies for the forecast of water resources has been analyzed and regular trainings have been provided [48,97]. The utilization of modern geo-information techniques has been established at all five Central Asian Hydromet services (personal communication with Baumgartner). Since 2011, the World Bank in cooperation with UN agencies and the World Meteorological Organization has been supporting the national hydro-meteorological services in the framework of the Central Asia Hydrometeorology Modernization Project (CAHMP), targeting at an improvement of monitoring infrastructure and early warning capacities [98]. The German Federal Foreign Office has been supporting a collaboration of the German and the Central Asian scientific community since 2008. The “Regional Research Network Central Asian Water” (CAWa) has been led by the GFZ German Centre for Geosciences and since 2014 particularly focused on developing hydro-climatic forecasting techniques and encouraging their use in the field of regional water management. Fully automated tools for the remote sensing based monitoring of snow cover, the forecast of summer discharge and the prediction of winter precipitation have been developed, partially in cooperation with regional experts, and provided to the respective departments [23,51,52]. Various on-the-job-trainings have been provided to forecasting experts at the national hydro-meteorological services. The trainings were designed as regional workshops (with participants from all Central Asian services) and thus, additionally served as a trans-national networking platform aiming at a strengthened regional cohesion. While some progress has been made (e.g. the snow cover monitoring tool ‘MODSNOW’ is nowadays in operational use at all five services and an exchange of hydro-meteorological data appears to be possible under certain circumstances), the modernization process remains slow and is characterized by setbacks. Despite the decadal long international engagement in the field of technical cooperation, the use of modern data sets and advanced statistical techniques is not yet integrated in the institutional workflows in a sustainable manner. This clearly indicates that successful capacity development requires a long-term commitment, and continuous coordinated effort. However, the institutional structures and the insufficient technical education of the regional experts represent further obstacles. In general, technical trainings address individual employees, however, high-skilled experts frequently leave the hydro-meteorological services after short time due to hierarchical institutional structures, low salaries and unclear promotion perspectives [29,87]. Others are promoted to higher positions, with larger administrative but limited technical responsibility. This brain drain effect makes regional capacity development a bottomless pit and calls for the establishment of transparent career pathways and mechanisms that support an internal knowledge transfer and a sustainable institutional learning.

The same applies in principle to stakeholder organizations in the fields of integrated water resource management, agricultural planning or risk assessment. Institutions at national and trans-national levels are frequently not aware of the opportunities and societal benefits of seasonal hydro-meteorological forecasts and multi-disciplinary or cross-sectoral networks are not yet well established. Thus, a better communication of the climate related vulnerability and the skill of modern forecasting techniques appears overdue. In this regard, science can contribute by developing user specific forecasting products that do not only include rather abstract hydro-climatic parameters, but directly address the associated risk. E.g. the mismatch in the spatial scales between regional precipitation predictions and the planning horizons of water managers (usually at catchment scale) leads to challenges in promoting the utilization of forecasting results [99]. User-tailored forecasts that directly relate expected precipitation anomalies to the likelihood of crop shortfalls and the associated financial risk will certainly better meet the user requirements. In any case, it is strongly recommended to strengthen the regional stakeholder networks in the water sector (possibly under direction of the national hydro-meteorological services), in order to stimulate the demand for hydro-meteorological information and thus to improve the outreach of seasonal climatic and hydrological predictions. Besides of its direct benefits for scientifically based water management, an increasing demand for hydro-climatological information may additionally encourage a structural change at the national hydro-meteorological services. While modernization so far has been mainly driven by technological developments, an increase and diversification of user requirements will likely stimulate leadership visions and may contribute to the development of the national centers towards client-oriented hydro-meteorological services. It should be noted, however, that a sustainable change of institutional structures cannot be achieved by science alone, but requires a long-term collaboration with international and regional organizations in the field of policy advice and international cooperation. It also calls for openness and readiness for transformation at the political level and respective governmental bodies.

Finally, in order to archive a long-term improvement of the capacity of young professionals, a stronger integration of modern methodological and scientific competencies (e.g. remote sensing, statistics, programming) into the water and climate related curricula at the local universities is urgently needed. Our experience has shown that a sustainable transfer of scientific knowledge into decision-making processes requires the involvement of the young generation that will shape the future practice in the field of water management. Recently, e.g the German-Kazakh University (GKU) established a course program on “Integrated Water Resource Management” that – although so far with international support – offers regular courses in the field of statistics, geo-information techniques and hydrological modelling. A long-term involvement of the international scientific community appears necessary to ensure a sustainable transfer of general scientific competences and cutting edge technologies to support their application in the field of water management in Central Asia.

5. Summary and discussion

All five Central Asian countries face water related challenges that directly or indirectly effect the regional economic development, the political stability and the ecological balance. Robust seasonal forecasts (and quantitative estimates of the available water resources in general) have the potential to improve the regional water management, especially in transboundary catchments. During recent decades, accurate techniques for the seasonal prediction of regional climatic conditions and water availability have been developed and their potential for scientifically informed decision-making in the water sector has been demonstrated. Particularly the forecast of discharge anomalies during the vegetation season based on the wintertime accumulation of snow in the high mountain regions has been shown to be exceptionally skillful. Nowadays, remote sensing derived data sets offer opportunities for an improved assessment of water resources and thus for the operational implementation of hydrological forecasting routines in trans-national catchments. Likewise, due to the predominant influence of ENSO, the Central Asian winter climate has been shown to be predictable to some extent. Although seasonal climate predictions are subjected to large uncertainties, they enable an assessment of the hydrological drought risk during the vegetation season already in preceding autumn and thus facilitate long-term planning in agriculture and trans-national water management. In summary, the well acknowledged vulnerability of the regional economies to water shortages in combination with the scientific progress in the field of seasonal forecasting clearly suggests a stronger integration of hydro-climatic information into decision-making processes at both, local and trans-national levels. However, despite the scientific progress and the continuous international effort with regard to knowledge transfer and regional capacity development, Central Asian water management institutes still rely on outdated forecasting techniques and modernization is proceeding slowly. To date, the national hydro-meteorological services do not fully meet the requirements of potential user groups and the dissemination of their seasonal forecasts is rather limited. Although the technical cooperation between the international scientific community and the national hydro-meteorological services in Central Asia has been successfully established during the last decades, the newly acquired knowledge is not yet sustainably incorporated into institutional workflows. Particularly institutional structures often impede sustainable institutional learning and knowledge anchoring over longer times. Furthermore, decision makers in the field of water management (e.g. reservoir managers, farmers, water basin organizations at local or trans-national scales) are frequently not aware of the scientific progress and its implication for an improvement of water management. Thus, the demand for robust hydrological and climatic predictions is limited and the integration of modern scientific knowledge into water policy and decision-making remains challenging.

While academic studies on the use of seasonal forecasts for informed decision-making in the water sector are rare, a significant number of scholars examined the role of scientific information for the implementation of an 'Integrated Water Resource Management' [12,84,100] and evaluated the success of international capacity development campaigns (Dedabaev, 2016). Most studies indicate that limited institutional reforms hinder the development of a sustainable water management, especially since the prevailing state-centric (top-down) management systems contradict local ownership and responsibility at the local scale [84,91,100]. Dadabaev [72] emphasizes the importance of regional trust and openness with regard to data and knowledge exchange for the successful adoption of IWRM and demonstrate that international efforts are currently restricted to individual capacity development at the local or national scale. Just like in the field of seasonal forecasting, data-scarcity, capacity deficits and inefficient governance structures including limited institutional funding and insufficient transboundary cooperation have been stressed as major challenges for the implementation of IRWM in Central Asia [22,91,101].

Against this background, a continuous and coordinated effort in the field of capacity development and knowledge dissemination at various institutional levels appears necessary to communicate potential of seasonal forecasts for an improved water management. We highly recommend to involve young academics, technical experts at the national hydro-meteorological services as well as an expanded circle of stakeholders and user groups in order to stimulate a multi-disciplinary network and to support a sustainable regional collaboration in the water sector. Such effort cannot be achieved by the science alone, but requires a long-term collaboration with international think tanks and global policy organizations.

Currently, a fresh political wind is blowing in Central Asia and regional collaboration has been recognized as an important basis for sustainable economic development. Particularly Uzbekistan is promoting a stronger regional integration and recently suggested the establishment of an 'International Innovation Center for the Aral Sea Basin' targeting at sustainable water governance and societal stability through innovative research and technology [56]. Kyrgyzstan is currently establishing a national water information system allowing access to water related data and information, including seasonal discharge forecasts and water allocation at the local scale [102]. Technical and scientific innovation in water management is more and more recognized as a joint Central Asian challenge and has the potential to stimulate the regional political integration. The continuation of the international scientific effort in the field of seasonal forecasting and knowledge dissemination can certainly strengthen this process.

CRediT authorship contribution statement

Lars Gerlitz: Conceptualization, Data curation, Formal analysis, Methodology, Validation, Visulaization, Writing - original draft, Project administration. **Sergiy Vorogushyn:** Resources, Writing - review & editing. **Abror Gafurov:** Resources, Writing - review & editing, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This work was undertaken within the frame of the CAWa project (www.cawa-project.net) funded by the German Federal Foreign Office as part of the German Water Initiative for Central Asia (grant number AA7090002). The authors would like to thank Dr. Michael F. Baumgartner (MFB-GeoConsulting, Solothurn, Switzerland) for sharing his experience within the Aral Sea Project (World Bank, Swiss Development Cooperation and Federal Office of Foreign Economic Afffairs). Finally, we would like to thank our colleagues at the five national hydro-meteorological services in Central Asia for their decadal-long collaboration that will be continued in future.

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